

# Thickness of Stellar Disks in Early-type Galaxies

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We suggest and verify a new photometric method enabling derivation of relative thickness of a galactic disk from two-dimensional surface-brightness distribution of the galaxy in the plane of the sky. The method is applied to images of 45 early-type (S0–Sb) galaxies with known radial exponential or double-exponential (with a flatter outer profile) surface-brightness distributions. The data in the  $r$ -band have been retrieved from the SDSS archive. Statistics of the estimated relative thicknesses of the stellar disks of early-type disk galaxies show the following features. The disks of lenticular and early-type spiral galaxies have similar thicknesses. The presence of a bar results in only a slight marginal increase of the thickness. However, we have found a substantial difference between the thicknesses of the disks with a single-scaled exponential brightness profile and the disks that represent the inner segments of the Type III (antitruncated) profiles. The disks are significantly thicker in the former subsample than in the latter one. This may provide evidence for a surface-brightness distribution of a single-scaled exponential disk to be formed due to viscosity effects acting over the entire period of star formation in the disk.

# 1 INTRODUCTION

Two main large-scale components of structure of any galaxy – a stellar bulge and a stellar disk – have different spatial geometries. Bulges are spheroids, with three axes of typically comparable length; while disks are flat stellar subsystems whose thicknesses are much smaller than their radii. However, the thickness of a stellar disk is not infinitely small, and the thickness and the radius of a typical galactic disk differ by less than an order of magnitude. The thickness of a stellar disk is an important physical parameter which can help to specify dynamical evolution of the galaxy: interactions with other galaxies such as gravitational tides or merging with smaller satellites, can “heat” the disks (e.g. [1, 2]), making them thicker, while smooth, laminar accretion of a large amount of cool gas with subsequent star formation and the development of young stellar systems that are dynamically cool like the gas from which they form, can reduce the thickness of the disk [3].

Observational studies of the thicknesses of stellar disks in galaxies have been based to date mainly on statistics of large inhomogeneous samples of galaxies. It was also assumed that the disks were characterized by random orientation in space, so that a distribution of apparent ellipticities of the disks seen in projection onto the plane of the sky carried information about the average ratio of the thickness to the radius. The latest statistical estimates of the average thickness of galactic disks  $q$  are based on the data from the SDSS: Padilla and Strauss [4] have analyzed a sample of several thousand galaxies with exponential brightness profiles – i.e., galaxies dominated by disks – using the Sixth Data Release of the SDSS, and they have obtained  $q = 0.21 \pm 0.02$ . The same team has obtained a somewhat higher estimate of  $q$ ,  $q = 0.267 \pm 0.009$ , by using naked-eye classifications of spiral galaxies from the Galaxy Zoo project, by selecting them from the 8th Data Release of the SDSS [5]. There are not very many individual, non-statistical estimates of the thicknesses of stellar disks. It is possible to measure the thickness of a stellar disk directly only if the galaxy is viewed edge-on. Let us note

that it is difficult to estimate other properties of the disk structure in this case, since all the material that is located in the equatorial plane is seen as integrated along the line of sight. In early studies of the surface-brightness distributions in the optical *BVRI*-bands in eight S0–Sd galaxies viewed edge-on [6], very thin disks were found: the ratio of the vertical and horizontal scalelengths for the brightness distributions were, on average,  $z_0/h = 0.17 \pm 0.01$ . However, this might be due to the small size of the sample. Recently, based on a decomposition of the near-IR images of some two hundred edge-on galaxies (*JHK*-band images from the 2MASS survey), Mosenkov et al. [7] found a very broad distribution of  $z_0/h$  with a median value close to 0.3. Meantime, the average thickness of galactic disks has no more meanings than the mean temperature in a hospital. Galactic disks can suffer very different dynamical evolution, due mainly to the density of their environment, as well as to the prominence and structure of the spheroidal components of the galaxy. Correspondingly, the distribution of disk thicknesses is far from a normal law. Estimate of individual disk thicknesses and their comparison with the statistics of other disk parameters, such as the surface-brightness profile shape, is much more interesting problem. This is the topic addressed in the present study. We propose here a new method, which we have used to estimate individual disk thicknesses in a sample of galaxies viewed at angles different from 90 degree. We have been interested in possible differences of disk thicknesses in galaxies with different radial surface-brightness profiles. We used the sample of galaxies and classification of the radial brightness profiles compiled in the papers by Erwin et al. [8] and Gutiérrez et al. [9]. In contrast to the classical study by Freeman [10], which reported strictly exponential surface-brightness distributions in the stellar galactic disks, Erwin with coauthors [8, 9] found that, in general, a disk surface-brightness profile can be represented by two exponential segments with different characteristic scalelengths. It is currently believed that single-exponential disks with a uniform scale (Type I), truncated disks (outer scalelength smaller than the inner one, Type II), and two-tiered disks (outer scalelength larger than the inner one, Type III) have different origins. Previously proposed scenarios of their formation

predicted definite consequences for the disk thicknesses. Thus, our results can be used to test theories of the formation and evolution of the galactic disks.

## 2 The Method

We have developed an original method which can be used to estimate relative disk thicknesses by using two-dimensional surface-brightness distributions of a galactic disk projected onto the plane of the sky. The method is applicable to galactic disks if (a) the disks are circular and (b) with exponential or double-exponential surface-brightness profiles. The disks are considered to be plane-parallel (within every exponential segment of the brightness profile), i.e., they have the same thickness at any distance from the center. We have assumed that the same exponential law for the fall of the volumetric stellar emissivity with radius is obeyed in the equatorial plane and at some distance from this plane. For the method to work correctly, it is also necessary that the galaxy not be viewed strictly face-on or strictly edge-on. The key idea of our approach is analysis of the surface-brightness distribution in the polar coordinate system and splitting the galaxy image into sectors. The azimuthal tracing of equal surface brightness (isophotes) and measurements of the exponential scalelength of the radial brightness profiles at different angles to the major axis of the isophotes provide discrete sets of points separated by equal angles in polar coordinates referenced to the center of the galaxy and its line of nodes. Both the isophotes and azimuthal changes of the exponential scalelengths were fitted by ellipses. This approach makes it possible to estimate independently the axis ratios of the isophotes and of the ellipses for the scalelengths; we find the relative disk thickness by comparing these two ellipticities.

### 2.1 The Main Formulae

Let us consider a galaxy with a round disk of radius  $a$ , with relative thickness  $q = d/a$  and inclination to the plane of the sky  $i$ . The ellipticity of the isophotes  $e_I$  of the image of this disk

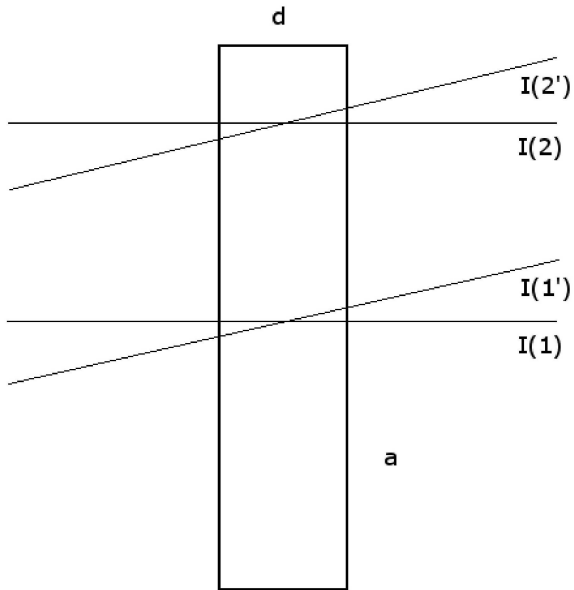


Figure 1: Sketch showing the integration of the disk stellar emissivity along the line of sight for various disk inclinations to the plane of sky. The disk is shown edge-on, and the observers line of sight lies in the plane of the picture.

is related to its thickness and inclination by the formula:

$$\sin i = \sqrt{\frac{2e_I - e_I^2}{1 - q^2}} \quad (1)$$

Let us assume that the disk surface brightness profile has an exponential shape, being expressed in the plane of a galaxy by a formula  $I(R) = I(0) \exp(-R/h)$  [10]. Let us compare the surface brightnesses near the points 1 and 2 (Fig. 1) for viewing along the rotation axis of the disk ( $I(1)$  and  $I(2)$ ) and at some angle to this axis ( $I(1')$  and  $I(2')$ ). We assume that the disk thickness  $d$  is constant with radius and that the radial scalelength  $h$  does not depend on the distance to the galactic plane (on the height). The surface brightness seen at a given point of the disk image is the integral of the volumetric emissivity along the line of sight. For the lines of sight corresponding to  $I(1)$  and  $I(2)$ , the volumetric emissivity in each element of the parallel segments of the lines of sight over which we are integrating have the same ratio:  $I(1)/I(2) = \exp(-\rho_{12}/h)$ . If  $d$  is constant along the radius and  $h$  is constant with height above the equatorial plane, the proportionality is retained in each element of the lines of sight corresponding to  $I(1')$  and  $I(2')$ . Therefore,  $I(1')/I(2') = \exp(-\rho_{12}/h)$ . Thus, the scalelength  $h$  measured along the line of nodes does not depend on the inclination of the line of sight to the galactic plane. Then, the scalelength  $h$  measured in the plane of sky at an angle to the line of nodes would decrease entirely due to the effect of projection, obeying to a cosine dependence on the polar angle. Thus, having derived an ellipse for the distribution of the apparent exponential scalelengths over the azimuth in the plane of the sky and after measuring the ellipticity of this ellipse,  $e_h$ , we can find the inclination of the galactic disk to the plane of sky,  $i$ , from the following relation:

$$\sin i = \sqrt{2e_h - e_h^2}. \quad (2)$$

Thus, substituting (2) into (1), we obtain the following work formula for deriving the

thickness of a galactic disk from the ellipticities of the isophotes and of the azimuthal distribution of the exponential scalelength:

$$q = \sqrt{1 - \frac{2e_I - e_I^2}{2e_h - e_h^2}}. \quad (3)$$

## 2.2 Steps of the Computations

Prior to the disk thickness calculations, the sky background was subtracted from the galaxy images, and foreground stars and other bright, compact features such as rings and starforming regions were masked.

An isophote radial position  $R_n(count)$  can be determined at different polar angles from the equation  $I_n(R_n) = count$  for a fixed signal level of  $count$ . An ellipse with the semi-major axis  $a_I$  and ellipticity  $e_I$  fitted to a set of 20  $R_n(count)$  points uniformly distributed over azimuth in polar coordinates,  $M_n(count) = (R_n, \frac{\pi n}{10} + \frac{\pi}{20})$ , describes the galaxy isophote at the brightness level  $count$ . We have divided the cleaned galaxy image into 20 sectors by the rays started from the galaxy center. We took the center at the brightest point of the image, and divided the image into 20 nonintersecting sectors with opening angle  $\pi/10$ . We constructed radial surface-brightness distributions  $I'_n(\rho)$  for every  $n$ th sector as the dependencies of the brightness  $I'$  averaged along the azimuth on the distance  $\rho$  from the center, by averaging  $I'$  over the azimuthal angles  $\varphi \in \left(\frac{\pi n}{10}, \frac{\pi(n+1)}{10}\right]$ . If the galaxy possesses central symmetry, the profiles  $I'_n(\rho)$  and  $I'_{n+10}(\rho)$  are identical, and it makes sense to increase the accuracy of measurements by considering only 10 profiles,  $I_n(\rho) = (I'_n(\rho) + I'_{n+10}(\rho))/2$ . Assuming an exponential shape of the radial dependencies for the disk surface brightness, we calculated the scalelength  $h_n$  for each of the 10 sectoral cross-sections. For this purpose, we fitted the straight line  $1.086(R_m/h) + l$  to the set of points  $(R_m, 2.5 \log I_n(R_m))$ , where  $R_m \in [R_{n0}(j), R_n(count)]$  by the least-square method. We have chosen the  $R_{n0}$  such as those with the smallest least-square scatter of the surface brightness measurements around the exponential law, individually

for each cross-section. Then,  $h_n = h(R_{n0})$  is the scale for the  $n$ -th cross-section in the radial range  $[R_{n0}(\text{count}), R_n(\text{count})]$ . The set of points in polar coordinates, representing exponential scalelengths in the different sectors,  $N_n = (h_n, \frac{\pi n}{10} + \frac{\pi}{20})$  is approximated by an ellipse with the semi-major axis  $a_h$  and ellipticity  $e_h$ . For every Type III galaxy, for which the full disk surface-brightness profile is approximated by two exponential segments, we constructed the isophotes and ellipses of the scalelength coefficients for each of the two exponential segments separately. The thickness of the disks was derived using (3).

### 3 The galaxy sample and photometric data used.

To test the method, we have taken a sample of galaxies with exponential and double-exponential disks which radial brightness profiles have been analyzed by Erwin et al.[8] and Gutierrez et al.[9]. The galaxies with bars were described in [8], and the galaxies without bars – in [9]. We have selected galaxies with single-scaled exponential disks (Type I) and with double-scaled exponential disks, where the scalelength of the outer disk is larger than the scalelength for the inner disk (Type III), from the total sample presented in [8, 9]. Our final sample includes 66 galaxies: 29 galaxies of Type I and 37 galaxies of Type III. The sample contains mainly early-type (S0–Sb) disk galaxies. We have retrieved digital images of the sample galaxies from the database of the SDSS photometric survey, Data Release 8 [11]. The images were found for 24 Type I and 19 Type III galaxies. We have also adopted archival SCORPIO data [12] from the 6-m telescope of the Special Astrophysical Observatory for NGC 2300 and NGC 2787. We have applied our method to the SDSS  $r$ -band images, which have the highest signal-to-noise ratio. It have appeared impossible to apply the method to NGC 2712 (Type I; the disk looks non-exponential), NGC 4045 (Type III; the inner disk is non-exponential, and the outer disk looks noisy), NGC 5806 (Type III; the inner disk displays a high intrinsic ellipticity), UGC 4599 (Type III; low signal-to-noise ratio has prevented to extract the low-surface-brightness disk). We have also added to our sample the galaxies NGC 4513 (Type III, was analyzed in [13]) and



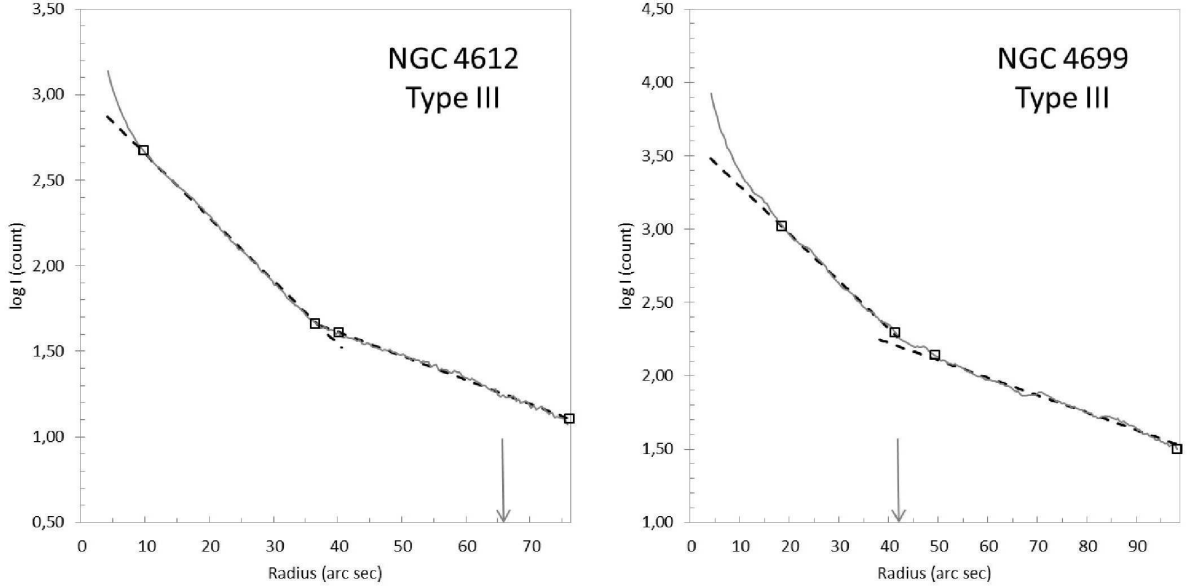


Figure 2: Double-exponential surface-brightness profiles of the Type III galaxies NGC 4612 and NGC 4699 in the SDSS  $r$ -filter. The arrows mark the  $R_{25}$ -radii.

NGC 4124 (Type I, was inspected in [14]). As a result, we have succeeded to apply our method to derive the relative disk thicknesses for 26 Type I galaxies, 17 inner disks of Type III galaxies, and 2 outer disks of Type III galaxies.

## 4 RESULTS

The accuracy of the SDSS data has appeared to be sufficient to derive the thicknesses of both the inner and outer disks for only two Type III galaxies: NGC 4612 and NGC 4699. Figure 2 presents the surface brightness profiles in the sectoral cross-sections along the major axes of the inner disks of these galaxies. The arrow marks the isophotal radius at the level of  $\mu_r = 23.5$ , that corresponds roughly to the optical galactic radius  $R_{25}$  where we have aimed to draw the reference isophotes. The outer disk of NGC 4612 is probably the main stellar disk, with the central surface brightness typical for disk galaxies [10], while the outer disk in

NGC 4699 is traced beyond the formal optical boundary of the galaxy and has low central surface brightness. Nevertheless, the outer-disk parameters in these galaxies are surprisingly similar: in both cases, the outer disks are thick ( $q = 0.52 - 0.56$ ), being much thicker than their inner disks ( $q = 0.19 - 0.26$ ). Since we already found a similar trend of the disk flaring while going outward along the radius, by measuring the inner and outer disk thicknesses of the Type III galaxy NGC 7217 from kinematic data [15], this result hints at some tendency, with the outer disks most often being thicker than the inner ones.

Table 1: Relative thicknesses of the stellar disks,  
found by our new photometric method in the galaxies of our sample.

Galaxy	Type(NED)	$R''_{25}$	Disk type	$h''$	$R''_0$	$R''_f$	$q$	$\delta q$
IC 676	(R)SB(r)0+	40	I-1	72	-	61	0.3790	0.0001
NGC 1022	(R')SB(s)a	61	I-1	56	-	97	0.808	0.012
NGC 2300	SA0 <sup>0</sup>	85	I-2	416	-	187	0.565	0.023
NGC 2787	SB(r)0+	95	I-1	85	-	114	0.230	0.008
NGC 3032	SAB(r)0 <sup>0</sup>	36	I-2	36	-	36	0.415	0.016
NGC 3169	SA(s)a	125	I-2	126	-	125	0.40	0.05
NGC 3485	SB(r)b	47	I-1	92	-	47	0.70	0.02
NGC 3489	SAB0 <sup>+</sup> (rs)	87	III-d-1	56	54	111	0.0	0.03
NGC 3599	SA0	16	I-2	34	-	30	0.706	0.007
NGC 3604	SA(s)a pec	41	III-d-2?	45	28	55	0.15	0.01
NGC 3607	SA(s)0 <sup>0</sup>	114	I-2	103	-	114	0.31	0.11
NGC 3619	(R)SA0 <sup>-</sup> (s):	81	III-d-2	82	42	82	0.22	0.03
NGC 3626	(R)SA(rs)0+	71	I-2	64	-	49	0.52	0.02
NGC 3898	SA(s)ab	94	III-d-2	77	41	81	0.175	0.007
NGC 3900	SA0 <sup>+</sup> (r)	67	III-d-2	70	50	100	0.195	0.008
NGC 3998	SA0 <sup>0</sup> (r)?	71	III-d-2	57	57	113	0.35	0.03
NGC 4124	SA0 <sup>+</sup> (r)	100	I-1	74	-	100	0.0	0.007
NGC 4138	SA0 <sup>+</sup> (r)	65	III-d-2	39	19	46	0.066	0.008
NGC 4150	SA0 <sup>0</sup> (r)?	45	III-s-2	30	32	68	0.0	0.004
NGC 4151	(R')SAB(rs)ab	90	I-1	90	-	90	0.45	0.04
NGC 4245	SB(r)0/a	65	I-1	78	-	88	0.687	0.006
NGC 4267	SB(s)0-?	74	I-1	76	-	74	0.48	0.01
NGC 4340	SB(r)0+	74	I-1	149	-	74	0.524	0.009
NGC 4371	SB0 <sup>+</sup> (r)	113	III-d-1	154	126	149	0.362	0.008
NGC 4459	SA0 <sup>+</sup> (r)	32	III-d-2	38	16	45	0.524	0.024

Galaxy	Type(NED)	$R_{25}''$	Disk type	$h''$	$R_0''$	$R_I''$	$q$	$\delta q$
NGC 4477	SB(s)0:?	114	I-1	85	-	88	0.69	0.03
NGC 4513	(R)SA0 <sup>0</sup>	26	III-1	28	14	26	0.245	0.004
NGC 4578	SA(r)0 <sup>0</sup>	72	I-2	79	-	72	0.0	0.02
NGC 4596	SB(r)0+	182	I-1	174	-	102	0.664	0.014
NGC 4612	(R)SAB0 <sup>0</sup>	68	III-d-1 (exter)	98	44	88	0.516	0.020
NGC 4612	(R)SAB0 <sup>0</sup>	68	III-d-1 (inter)	38	10	40	0.192	0.006
NGC 4643	SB(rs)0/a	105	I-1	182	-	104	0.73	0.02
NGC 4665	SB(s)0/a	107	I-1	145	-	106	0.812	0.007
NGC 4691	(R)SB(s)0/a pec	71	III-d-1	105	32	65	0.715	0.013
NGC 4699	SAB(rs)b	130	III-d-1 (exter)	98	49	98	0.564	0.007
NGC 4699	SAB(rs)b	130	III-d-1 (inter)	34	18	42	0.258	0.013
NGC 4754	SB(r)0-:	114	I-1	129	-	113	0.34	0.02
NGC 4772	SA(s)a	107	I-2	116	-	106	0.31	0.02
NGC 5485	SA0 pec	58	I-2	55	-	58	0.43	0.02
NGC 5520	Sb	37	I-2	38	-	36	0.214	0.014
NGC 5740	SAB(rs)b	61	III-d-1	46	27	69	0.0	0.018
NGC 5750	SB(r)0/a	70	I-1	42	-	70	0.0	0.012
NGC 7177	SAB(r)b	53	III-d-1	42	34	49	0.16	0.04
NGC 7457	SA0 <sup>-</sup> (rs)?	92	III-d-2	48	12	27	0.20	0.02
NGC 7743	(R)SB(s)0+	57	I-1	68	-	75	0.50	0.04

The results of disk thickness measurements for our total sample are presented in the Table, whose columns contain (1) the galaxy name, (2) the morphological type according to the NED database, (3) the semi-major axis of the galaxy optical image according to the NED data, (4) the type of the surface brightness profile over the disk according to [8, 9], (5) the exponential scalelength along the disk line of nodes according to our results, (6) the assumed inner boundary of the disk in Type III galaxies, (7) the major-axis radius at which the reference isophote was drawn, (8) the relative disk thickness,  $q \equiv z_0/h$ , according to our results, and (9) the statistical uncertainty of the relative disk thickness  $q$ .

Next several plots show the statistics of our results on the relative thicknesses of the stellar disks, presented as histograms. The abscissa traces the disk thickness  $q$ , and the column heights correspond to the number of disks with a specified thickness in the subsamples. Galaxies for which the ellipticities of the isophotes and scalelength projection distributions are close enough

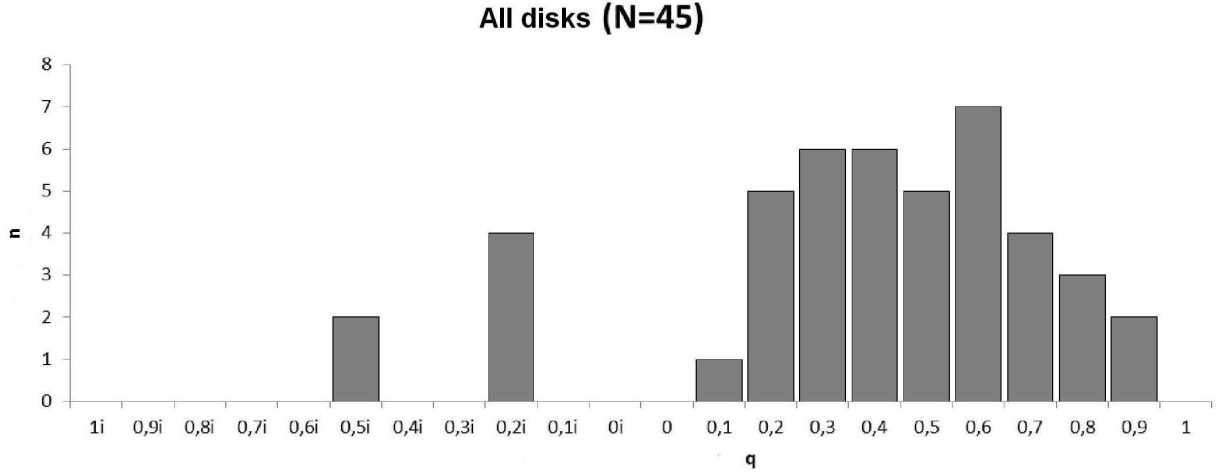


Figure 3: The distributions of the relative thicknesses  $q$  for all the stellar disks analyzed. The “complex” region to the left contains objects that have formally negative arguments of the square root in (3); these are either very thin disks with  $q \approx 0$ , which ended up in the  $0.2i$ -bin due to the statistical uncertainty in  $q^2$ , or disks whose intrinsic shapes suffer notable non-axisymmetry – two disks in the bin  $0.5i$  can be probably attributed to those.

so that the argument of the square root in (3) may be formally negative due to the statistical uncertainty in  $q$ , are plotted against negative  $q$  values. We take such disks to be infinitely thin, but plot them to the left from zero, in the “complex” range.

At the histogram for the whole sample (Fig. 3), the mean disk thickness is 0.38. The histogram for the whole sample is very broad, with relative thicknesses ranging from 0 to 0.9. If we divide the whole sample into two subsamples according to the profile type of the disks, the distributions for the subsamples appear to be much narrower. Figure 4 shows that the distribution of the inner-disk thicknesses for the Type III galaxies and that of the disk thickness for the Type I galaxies have shifted maxima. The inner disks of the Type III galaxies have a mean thickness of 0.19, while the disks of the Type I galaxies have a mean thickness of 0.48. Despite the small sizes of the subsamples, the Kolmogorov-Smirnov test indicates that the probability that the disks of Type I galaxies and the inner disks of Type III galaxies belong

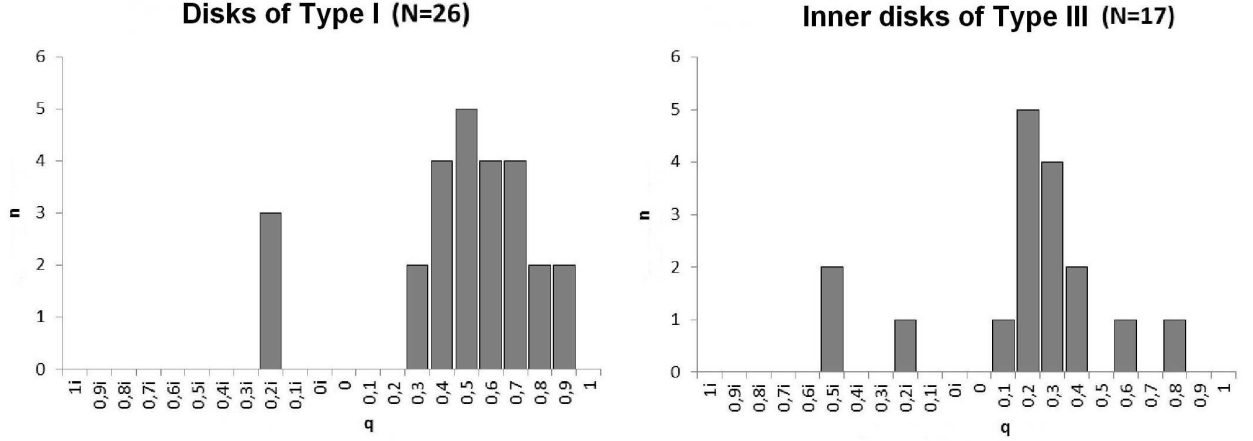


Figure 4: Comparison of the relative disk thicknesses in the Type I galaxies (single-exponential disks) and in the inner disks of the Type III galaxies (two-tiered double-exponential disks).

to the same parent sample is only 0.7%; i.e., the relative disk thicknesses for Type I and Type III galaxies are significantly different, with Type I galaxies (exponential disks with a unique scalelength) having thicker disks.

It is interesting that if the galaxies are separated into lenticular and spiral galaxies, or into galaxies with or without bars, the difference in the disk thicknesses between the subsamples is not so significant. For example, the mean disk thickness for the lenticular galaxies without bars is 0.26, while the lenticular galaxies with bars have a mean disk thicknesses of 0.46 (Fig. 5). However, both subsamples show a large scatter of the thicknesses. The Kolmogorov–Smirnov test indicates that the probability for the galaxies with and without bars to belong to the same parent distribution in terms of their disk thickness is 38%. If we consider the SA0 and SB0 galaxies as one subgroup (S0) and compare them to the early-type spiral galaxies, the significance of the difference becomes even lower. The mean relative disk thickness for all the lenticular galaxies is 0.36, and for the spiral galaxies 0.38 (Fig. 6). The Kolmogorov–Smirnov test indicates that the probability that these histograms are drawn from the same parent

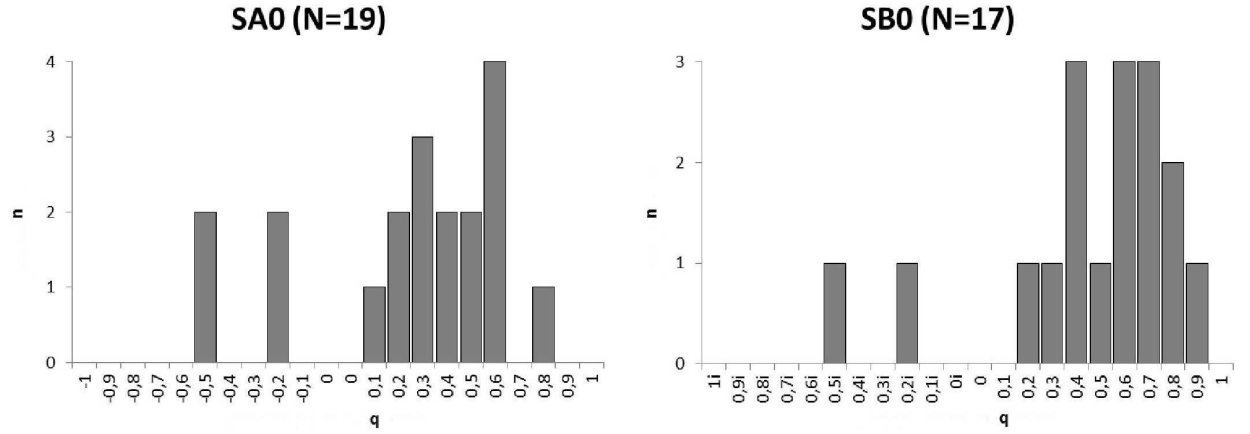


Figure 5: Comparison of the distributions of the relative disk thicknesses in lenticular galaxies with and without bars – SB0 versus SA0.

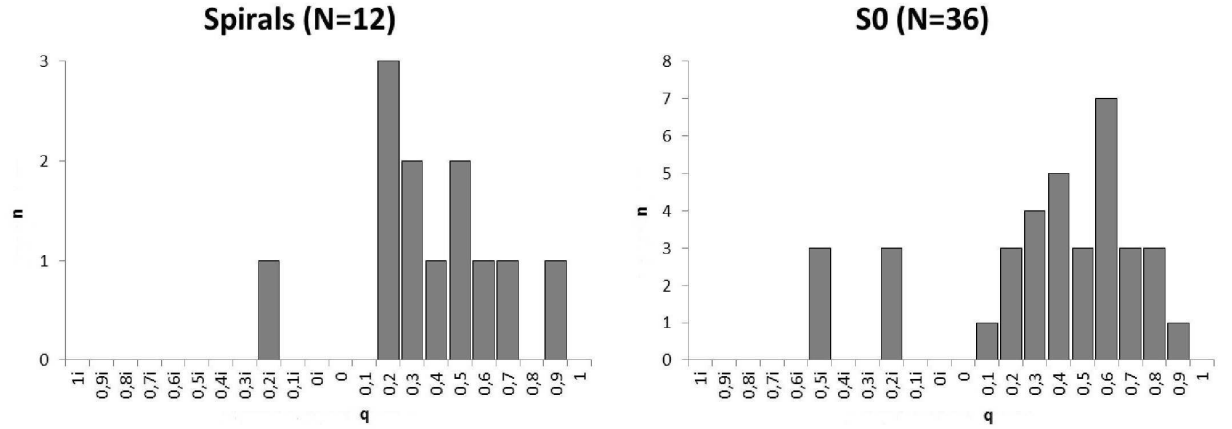


Figure 6: Comparison of the distributions of the relative disk thicknesses in lenticular and early-type spiral (Sa–Sb) galaxies.

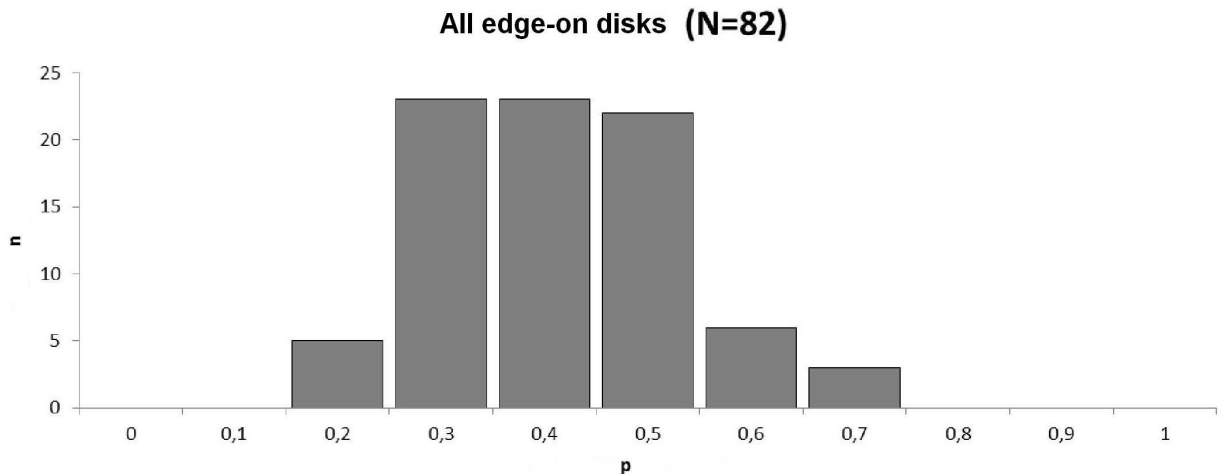


Figure 7: The distribution of the relative disk thicknesses for the edge-on galaxies from the sample by Mosenkov et al. [7] (the morphological types S0–Sb and the parameters in the NIR  $J$ -band are taken).

distribution is 99.5%.

## 5 THE COMPARISON OF OUR RESULTS WITH EARLIER STATISTICS

We have compared our results with some earlier statistics concerning the sample of edge-on galaxies compiled by Mosenkov et al.[7], who considered a sample of galaxies from the 2MASS survey which were selected according to following criteria.

1. The galaxies are seen strictly edge-on,  $i = 90^\circ$ .
2. The axis ratio of the image in the co-added  $J + H + K$  frame exceeds 0.2.
3. The radius of the galaxy measured in the  $K$ -band  $R_{Kron} > 30''$ .
4. The galaxies seem to be non-interacting.

## 5. The concentration index exceeds 2.0.

This approach had provided a sample of 175 disk galaxies of all types, whose *JHK*-images were decomposed into disks and bulges by using an original algorithm. Along the radius, the surface brightness profile was fitted by an exponential law with a single scalelength  $h$ , and the vertical decrease of the surface brightness from the equator outside was approximated by a squared secant law with a scale  $z_0$ . The ratio of our parameters  $a$  and  $d$  and the ratio of the scalelengths  $h$  and  $z_0$  are different characteristics. Nevertheless, it is interesting to compare the distributions of  $d/a$  and  $z_0/h$ , which are in fact various estimators of the relative thicknesses of the galactic disks. We have extracted early-type disk galaxies (S0–Sb) from the whole sample [7], and have calculated  $p = z_0/h$  by using quantitative estimates of the disk parameters kindly provided to us by Dr. N.Ya. Sotnikova in the tabular form. We are presenting here the histograms of the  $p$  distributions for the resulting subsample of 82 early-type disk galaxies. The mean relative thickness over the full subsample is 0.41 (Fig. 7); the scatter of these values around the mean is not too large – about 83% lie between 0.3 and 0.5. Nevertheless, although the mean disk thicknesses for our sample and for the sample [7] are similar, the Kolmogorov–Smirnov test indicates that the probability that our total sample and the subsample from [7] belong to the same parent sample is only 1.7%. The mean disk thickness for the subsample [7] is the most close to our subsample of Type I disks, but they are also statistically distinguishable. This may be associated with the small size of our sample of Type I galaxies. Dividing the subsample [7] into two ones according to the morphological types of galaxies does not result in appreciable changes in the character of their distribution, as it has been shown for our own subsamples. The mean disk thicknesses of lenticular and edge-on spiral galaxies are not significantly different: 0.40 versus 0.42 (Fig. 8). This is also in qualitative agreement with our results. However, the histogram widths for these two galaxy subsamples are substantially different: only 76% of lenticular galaxies have  $p$ -values between 0.3 to 0.5, while for the spiral galaxies the distribution of the thicknesses is more narrow: 89% of them have  $p$ -values in the



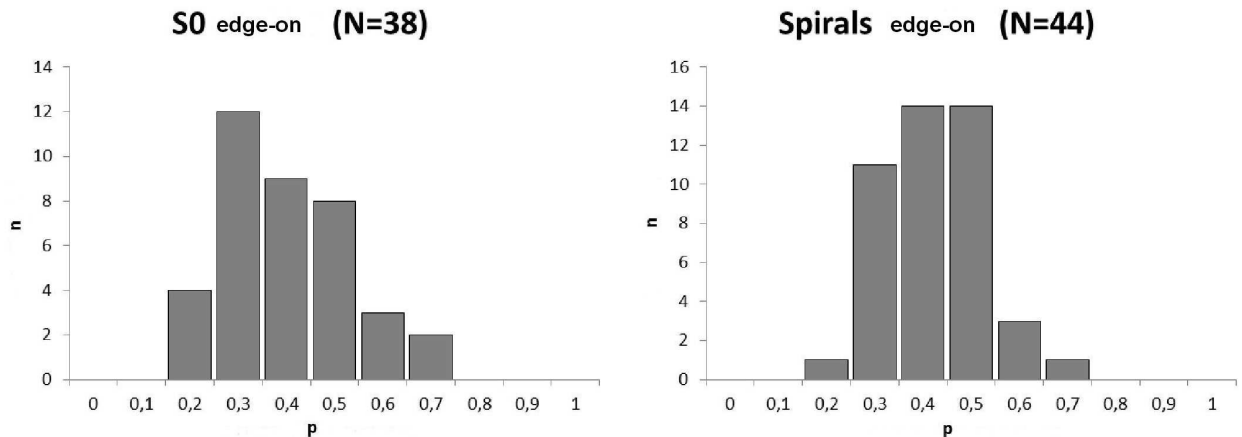


Figure 8: The comparison of the distributions of relative disk thicknesses for edge-on lenticular and spiral (Sa–Sb) galaxies by analyzing the decomposition results of their J-band images from [7].

range [0.3, 0.5]. The Kolmogorov–Smirnov test indicates an absence of significant differences between the disk thicknesses for galaxies of various morphological types: the probability that both subsamples belong to the same parent distribution is 76%. Thus, our sample and the sample [7] are similar in the sense that, among early-type disk galaxies, there is no significant difference in the disk thicknesses of lenticular and spiral galaxies.

## 6 CONCLUSIONS AND DISCUSSION

In this work we propose a new photometric method to derive relative thicknesses of galactic disks from their two-dimensional surface-brightness distributions projected onto the plane of the sky. We have applied this method to 45 early-type (S–Sb) disk galaxies with purely exponential (Type I according to [8, 9]) or double-exponential, with a flatter outer profile (Type III according to [8, 9]). The obtained statistics on the relative disk thicknesses of early-type galaxies reveals a lot of interesting features. On average, the stellar disks of lenticular and early-type spiral

galaxies have similar thicknesses. A bar presence results in only marginal thickening of the disks. However, there is a significant difference between the thicknesses of the disks with single-exponential brightness profiles and the inner parts of the disks with Type III profiles (i.e., with outer exponential disks having larger scalelengths). The disks are significantly thicker in the former than in the latter case.

How can we explain these similarities and differences in the frame of current ideas about the formation and evolution of the stellar disks in galaxies? The nature of the exponential brightness (density) profiles of the stellar galactic disks remains still a mystery. In the recent observational study Hunter et al.[16] noted that a single-scale exponential profile can be traced over the whole galaxy, covering the areas with very different star-formation modes and timescales. This contradicts apparently the idea that an exponentially-shaped density profile develops gradually in the course of the disks evolution, and provides some evidence for a scenario where primordial exponential density profile with a fixed scalelength is a necessary initial condition for the evolution of a stellar disk. However, if star formation proceeds through different modes and different timescales over different regions of a galaxy, why is the initial density profile not “smeared out” over a timescale of a few Gyr through the disk secular evolution?

A completely opposite paradigm developed analytically by Lin and Pringle [17] and later elaborated in numerical models in [18] seems to be more physically motivated as concerning the stellar disk thickness evolution as well. These studies considered a violent radial gas redistribution, simultaneous with the star formation. If a gaseous galactic disk is hardly viscous and if the viscosity timescale is comparable to the star formation timescale, an exponential profile of the stellar disk is naturally formed. This model is not very popular, mainly because the viscosity is required to be too strong. However, at high redshifts,  $z > 2$ , when relatively cool gas contributed a dominant fraction of baryonic matter in galaxies, and gaseous clumps with a range of sizes formed in the disks due to various instabilities and were suspended in more diffuse gas, the viscosity could be considerably stronger than it is known at the current epoch.

Through investigation of the stellar populations at the centers of galaxies with single-exponential disk-brightness profiles (Type I), we received already some hints that radial gas inflow into the centers of galaxies had to be especially intense in Type I disks. We found chemically distinct nuclei with abnormally large metallicity differences between the nuclei and the bulges in the Type I galaxies [19]. If the Type I galaxies experienced the most violent radial gas redistribution during their secular evolution, it seems possible that the same processes that removed the angular momentum of the gas (transient bars of a tidal nature, for example) also heated dynamically the stellar disks. This could explain the presence of the thicker stellar disks in these galaxies.

The origin of Type III disks is currently explained by minor mergers, following the dynamical simulations by Younger et al.[20]. Their models showed that outer exponential segments of the disk brightness profiles (which have larger exponential scalelengths in the case of Type III galaxies) are built up during the event by old stars of the primary (“parent”) disk galaxy, which were undergoing violent outward migration due to dynamical tides from a satellite that impacted the disk. If the absorbed satellite contained also gas, it may concentrate in the central region of a galaxy and, after a subsequent star formation burst, adds a young, cool stellar population to the inner disk. This scenario can qualitatively explain the small thicknesses of the inner disks of the Type III galaxies and also the fact that, when we are able to investigate both segments of a Type III profile, the outer disks have often larger thicknesses than the inner disks.

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